

# A Survey for EHB Stars in the Galactic Bulge

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## ABSTRACT

We present a progress report on an extensive survey to find and characterize all types of blue horizontal-branch stars in the nuclear bulge of the Galaxy. We have obtained wide, shallow imaging in  $UBV$  of  $\approx 12$  square degrees in the bulge, with follow-up spectroscopy for radial velocities and metal abundance determinations. We have discovered a number of metal-rich blue HB stars, whose presence in the bulge is expected by the interpretation of the extragalactic ultraviolet excess. Very deep images have been obtained in  $UBV$  and SDSS  $u$  along the bulge minor axis, which reveal a significant number of EHB candidates fainter than  $B = 19$ , i.e., with the same absolute magnitudes as EHB stars in several globular clusters.

## 1. Introduction: EHB stars and the bulge

This meeting is mainly concerned with very hot stars on the extreme or extended horizontal branch (EHB). It is important, however, to place these stars in the wider context of the formation and evolution of the entire blue horizontal branch (BHB), here meaning HB stars that are hotter than the RR Lyrae instability strip.

As we will hear at this meeting, EHB stars are common in the local field, and have been discovered in several globular clusters and a few open clusters. Among the globulars, only those with metallicity  $\leq 0.05$  solar ( $[\text{Fe}/\text{H}] \leq -1.3$ ) have hot BHB stars in abundance. In contrast,

very few are found in intermediate-metallicity systems such as 47 Tucanae, but they have been discovered in small numbers in two metal-rich globulars (Rich et al. 1997; Sosin et al. 1997).

The well-known phenomenon of the ultraviolet (UV) upturn (Code & Welch 1979; Bertola et al. 1980; O’Connell et al. 1986; Deharveng et al. 2002) in massive ellipticals and the bulges of other spirals tells us that old, metal-rich stellar populations can make significant numbers of hot stars (see other contributions to this conference). The generally accepted sources of the UV light are the EHB stars at the very hot end of the horizontal branch, the subdwarf B (sdB) stars and their shorter-lived progeny (O’Connell 1999). The numbers or lifetimes of EHB stars must increase with metallicity, since the far-UV flux does (Faber 1983; Burstein et al. 1988; Longo et al. 1989).

Locally, metal-rich BHB stars do exist. In the old open cluster NGC 6791, Liebert et al. (1994) find sdB stars, and Peterson & Green (1998) confirm a proper-motion and radial velocity member as a metal-rich ( $[\text{Fe}/\text{H}] = +0.4 \pm 0.1$ ) star on the cool BHB. But even in this massive open cluster, the EHB is too sparse to determine many details of the evolution of these stars: the lifetimes of these evolved stars are too short.

Globular clusters have a different relationship between metallicity and UV light from bulges or elliptical galaxies, as illustrated in Figure 1. This plots the strength of the UV excess (from the  $1550 \text{ \AA} - V$  color) against metallicity (from the  $\text{Mg}_2$  index of Faber et al. 1985). The open points are for Galactic globular clusters (Dorman et al. 1995); the one with the lowest far-UV flux is 47 Tucanae. The triangles show ellipticals and spiral bulges from Burstein et al. (1988). The filled triangles on Figure 1 are, in order of increasing  $\text{Mg}_2$ , for M 32 and M 31. At present, there is no direct measure of the  $1550 \text{ \AA}$  flux in the bulge because of the high interstellar extinction at low galactic latitudes, but there is a measurement of the integrated  $\text{Mg}_2$  index in the Baade’s Window field of the bulge, 500 pc from the galactic center (Idiart et al. 1996). This is shown as a vertical line in Figure 1, and indicates the range of UV fluxes expected from the inner bulge. Perhaps not surprisingly given the luminosity of the bulge, we can then expect that the bulge will contain more EHB stars per volume than M 32, where EHB stars are known to exist (Brown, this conference), but fewer than in M 31.

Furthermore, the bulge is a good example of an old, metal-rich population akin in density and star formation history to that in elliptical galaxies and the bulges of other spirals (Frogel & Whitford 1987; Frogel et al. 1990). Abundances in the inner bulge span  $[\text{Fe}/\text{H}] = -1.0$  to  $+0.3$ , with many stars showing enhanced light-element abundances (Whitford & Rich 1983; McWilliam & Rich 1994; Castro et al. 1996; Sadler et al. 1995). This resembles models of elliptical galaxy formation (Yoshii & Arimoto 1987) and interpretations of the integrated optical spectrum of the central regions of external galaxies (Worthey 1992; Worthey et al. 1992). The radial metallicity gradient in the bulge (Terndrup 1988; Terndrup et al. 1990; Tiede et al. 1995) provides a natural testbed of how metallicity drives BHB formation. The bulge is massive enough to support a large BHB population, perhaps including the short-lived progeny of EHBs. Stars of all types can be counted and analyzed, allowing a direct determination of the contribution of BHB and EHB stars

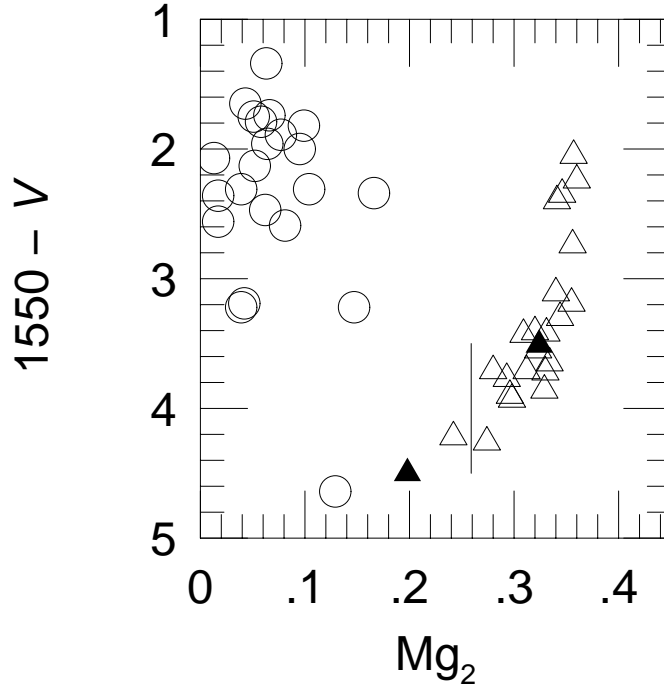


Fig. 1.— Strength of UV emission vs. the  $Mg_2$  metallicity index in globular clusters of the Galaxy (open circles), and in ellipticals and spiral bulges (triangles). The filled triangles are for M 32 (left) and M 31 (right). The vertical line shows the value of  $Mg_2$  measured for the bulge.

to the UV fluxes of the centers of galaxies; hot HB stars can seriously affect the determination of ages and metallicities deduced for these systems from their integrated optical or UV spectra (Ponder et al. 1998; Peterson et al. 2003).

## 2. Survey strategy

We have been conducting a survey which will yield complete samples of BHB stars of all temperatures. There are several components to this survey:

- 1) Wide-field, shallow imaging with the CTIO Schmidt telescope to identify BHB stars down to a limiting magnitude of  $B \approx 19$ . This is not sufficient to find the EHB stars that would create the UV flux (below), but it does generate large samples of cooler ( $T_{\text{eff}} \leq 15000$  K) BHB stars for follow-up spectroscopy to determine metallicities. In addition, we have time-series photometry with the Schmidt on several lines of sight to identify RR Lyraes, whose large excursions in temperature (or non-simultaneous  $UBV$  photometry in the survey) could land

them in our samples of BHB stars.

2) Fiber spectroscopy of BHB stars selected from the Schmidt survey. Stellar temperatures, gravities, and abundances are derived from spectral synthesis. Reddening is found by comparing observed colors with those predicted for the resulting stellar model. Distances follow from the apparent magnitude, providing with the radial velocities a check of membership in the bulge. A particularly important metallicity indicator is the Mg II  $\lambda 4481$  Å line, which is not strongly affected by radiative levitation for  $T_{\text{eff}} \leq 16000$  K (Behr et al. 1999). Most evolutionary models (e.g., Yi et al. 1997, 1998) predict that mechanisms of producing EHB stars at high metallicity will also cooler ( $T_{\text{eff}} \sim 10000$  K) metal-rich BHB stars as well.

3) Deep imaging in *UBV* and SDSS *u* along the bulge’s minor-axis with the CTIO Mosaic camera on the Blanco 4m telescope, to identify and determine the spatial distribution of faint EHB candidates.

The lines of sight in our survey are illustrated in Figure 2.

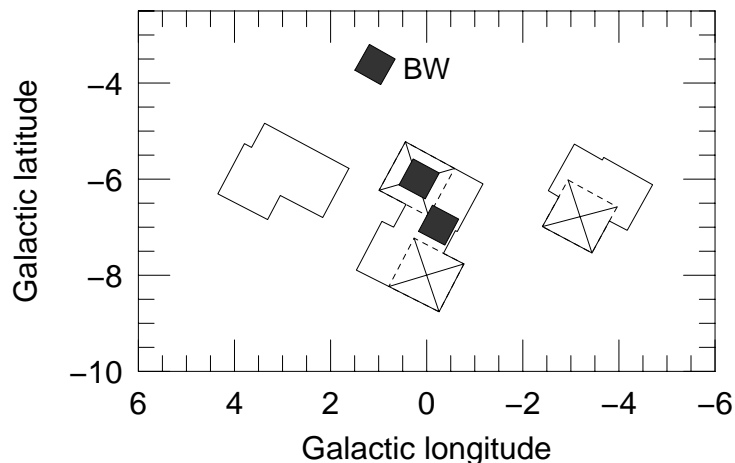


Fig. 2.— Location of survey regions in the bulge. The polygons outline the areas surveyed with the CTIO Schmidt for the cooler, brighter BHB stars. The squares marked  $\times$  indicate the fields with AAT spectra in 2001; the off-axis one was also observed in 1997 (Peterson et al., 2001). The shaded smaller squares mark fields with the Mosaic imaging from CTIO in 2001. BW designates the Baade’s Window field.

### 3. Some results and future plans

The first results from our survey were presented by Peterson et al. (2001), who obtained 2dF spectra at  $2.4$  Å resolution of 130 stars distributed all across the bulge CMD. 47 stars proved to be hot, and 37 were BHBs. They derived temperatures and metallicities for these by comparison to synthetic spectra based on the Kurucz (1993) models. Temperatures were set independently of

reddening using the central profile (but not the core) of the Balmer lines  $H\beta$ ,  $H\gamma$ , and  $H\delta$  where necessary. Most of the BHB stars were metal-poor, but two had abundances of solar or higher.

In 2001, we returned to the 2dF and obtained spectra of over 1000 BHB candidates on three lines of sight (see Fig. 2). The sample selection included mainly fainter BHBs than previously. Most of the sample has  $S/N > 40$  down to  $B = 17.5$ . Analysis of these spectra is underway. A preliminary comparison of the spectra against empirical templates in NGC 6752 obtained on the same observing run reveal a few sdB candidates, some of which may have composite spectra indicating a cooler companion like many field sdB stars (Saffer et al. 2000); at these magnitudes sdB stars are likely to be foreground objects. A few metal-rich BHB stars are seen, but most are metal poor as was found in the earlier survey. Preliminary results from the search for RR Lyraes in these fields show that only a few percent of the BHB stars are likely variables.

The main result relevant to this meeting is shown in Figure 3, which displays a color-magnitude diagram (CMD) in  $B$  and  $B - V$  for the field at  $(\ell, b) = (+0^\circ, -6^\circ)$ . The axes are marked “instrumental” because we are still working out the final details of the photometric calibration at the  $\approx 0.1$  mag level. The CMD shows the usual features one sees on lines of sight toward the bulge (e.g., Terndrup (1988); Kiraga et al. (1996)), namely a prominent giant branch and clump, and a foreground sequence of main-sequence dwarfs. In addition, there is an extended blue HB, with bluer colors than the foreground sequence and which extends down to below  $B = 20$ .

The faintest stars on the blue HB are as faint as the confirmed EHB stars in globular and open clusters ( $M_V \geq +4$ ). In the metal-rich open cluster NGC 6791, for example, sdB stars are found at  $B = 17.9$ ,  $B - V = -0.1$ . The cluster is 4.8 kpc distant ( $m - M_V = 13.42$ ), with  $(B - V) = 0.1$  (Chaboyer et al. 1999). Were the cluster located at a distance of 8 kpc with  $E(B - V) = 0.5$ , the sdB stars would be found at  $B \approx 20.8$ ,  $B - V = 0.4$ , or  $V = 20.2$ . The CMD in Figure 3 reaches nearly a magnitude fainter.

We also note that the bulge HB in all the currently reduced MOSAIC fields appears to have a gap around  $B = 18$ ; there are a large number of cool BHB stars, many faint and blue stars, and markedly little in between. This gap occurs at  $M_V = +2$ ; similar features are seen in the CMDs of several globular clusters.

The most important remaining observational goal is to see whether the faint, blue stars we find on the MOSAIC CMDs are bulge EHB stars. We know from our 2dF spectra that the majority of the BHB stars bluer than the foreground disk and with  $B \leq 18$  are probably in the bulge, though there are also likely to be halo HB stars at larger distances and the occasional foreground A-type main-sequence star as found by Peterson et al. (2001). We do not currently have spectra for the faintest candidates on Figure 3 to confirm their status as EHB stars in the bulge. While the spectroscopy would be challenging, one could get a reasonable sample since the surface density of these faint EHB candidates is well suited for the current generation of multifiber spectrographs: in the field shown in Figure 3, there are several dozen targets in an area approximately  $26 \times 26$  arcmin.

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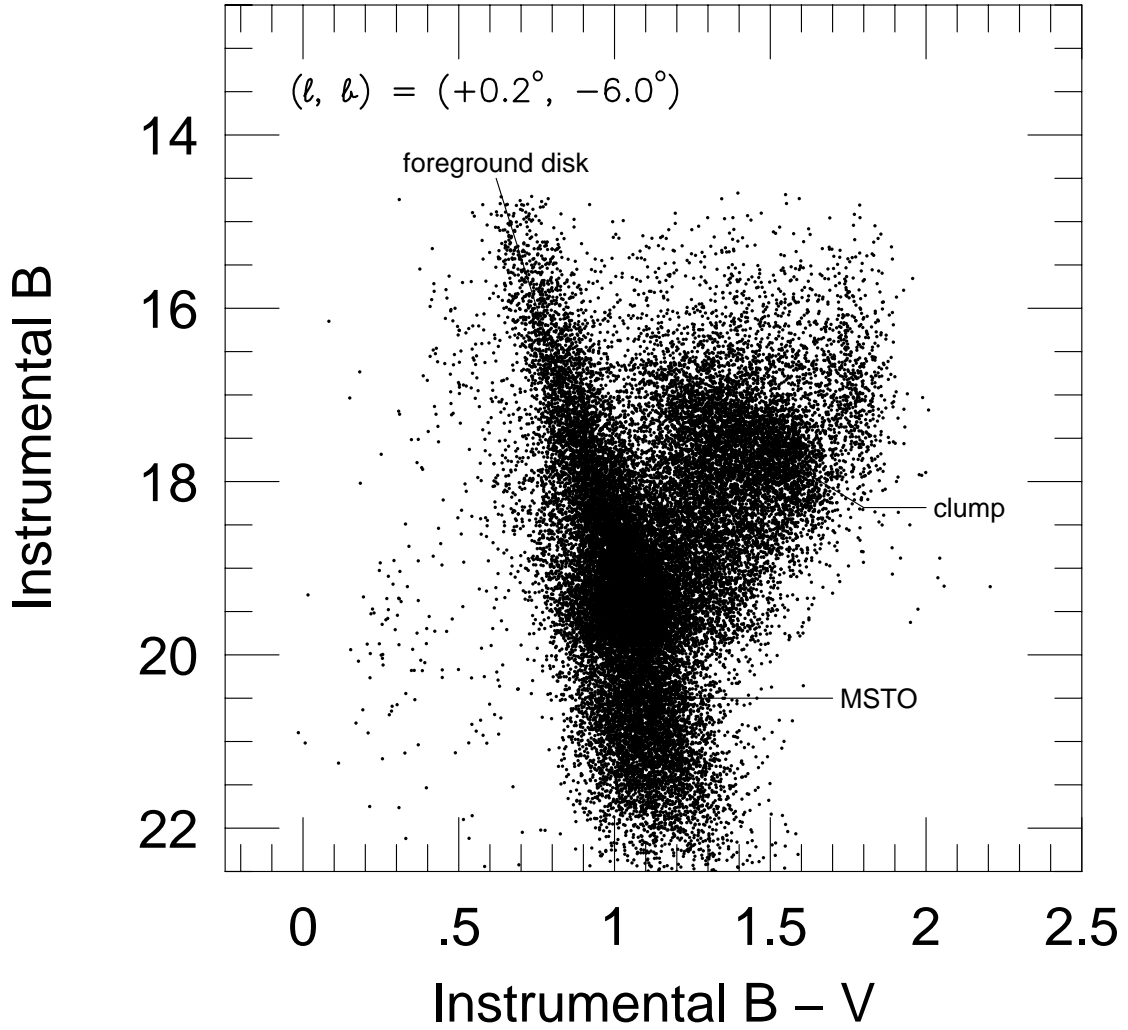


Fig. 3.— CMD for part of the CTIO MOSAIC field at  $(\ell, b) = (0^\circ, -6^\circ)$ . The total area covered by this reduction is 680 square arcmin. The zero point and color terms in the reduction are not yet finalized. The HB extends blueward of the sequence of foreground stars, turning downward below  $B \approx 17$ . The photometry has not been corrected for the (patchy) reddening, which averages about  $E(B - V) = 0.4$  in this field. The principal features of the CMD are marked; “MSTO” indicates the level of the bulge main-sequence turnoff. Only about 10% of the stars near the turnoff are shown in this figure.